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Concentrated solar power: Current technologies, major innovative issues and applicability to West African countries

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A B S T R A C T

Conventional Concentrating Solar Power (CSP) technologies have been mainly developed during the eighties. They can be considered as similar to conventional thermal power processes in which the boiler has been replaced, at least partially, by a concentrated solar field producing the heat. After more than 20 years of reduced activity, they have recently taken advantage of an impressive removal at the beginning of the new XXIst century and are subjected today to an increasing industrial interest. Based on the inherited technologies, companies build currently plants in the range of 10–20 MWe for central receiver CSP and 50 MWe for solar trough CSP. According to the IEA, at least 630 GWe of CSP should be installed in 2050 for only 700 MWe available today and preferably in areas of high solar potential (the so-called solar belt). Before this high potential, major issues have still to be overcome to enhance the performances and to adapt the technologies to the up to date constraints. In the present paper, the history and the technologies of the current CSP are presented, the major innovative issues described and the applicability to West African countries discussed. CSP standards proposed by developed countries are compared to the actual needs and potentials of West African countries.

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1. Introduction

Basically, CSP or Concentrating Solar Power, is no more than a conventional thermal power plant in which the boiler has been replaced by a large surface of optical devices able to concentrate

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the incoming diluted solar flux to produce steam to be turbined. When the solar incident flux is not high enough (on such systems only the direct radiations can be used) or even during night, a conventional boiler using various fuels can be used. An alternative approach consists to over scale the solar field with respect to the power block in order to store the excess heat produced during the sunniest hours and to discharge this heat during less sunny ones. Then, the power block can be advantageously fed at constant thermal power leading to higher efficiency and reduced maintenance. This thermal storage is one of the best potential

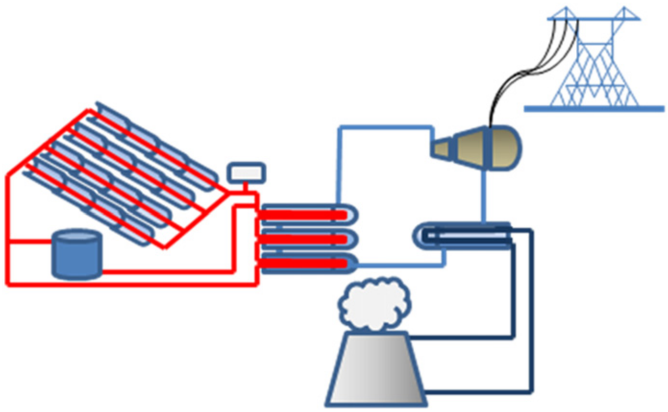

Fig. 1. Solar trough CSP technology, general layout.

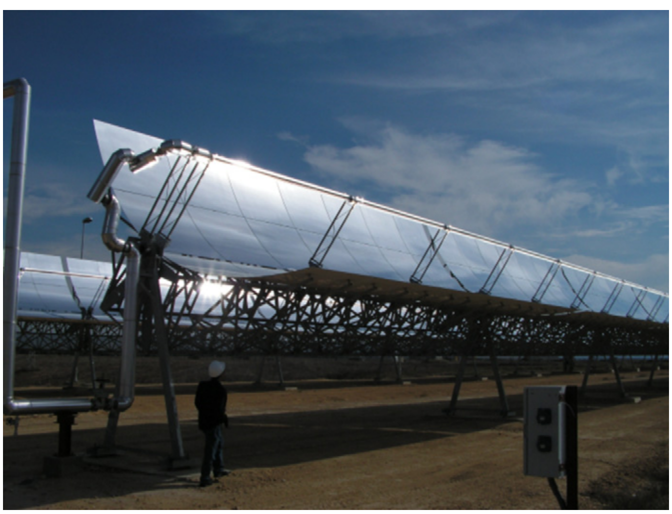

Fig. 2. Solar trough CSP technology, solar field.

Fig. 3. Linear Fresnel CSP technology, solar field.

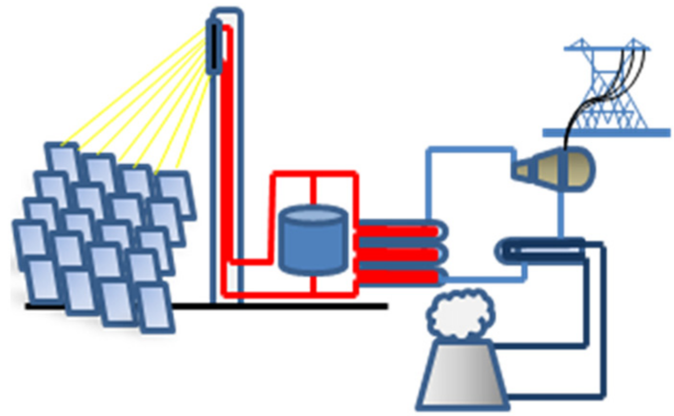

Fig. 4. Central receiver tower CSP, general layout.

Fig. 5. Central receiver tower CSP, Themis tower CSP pilot (France).

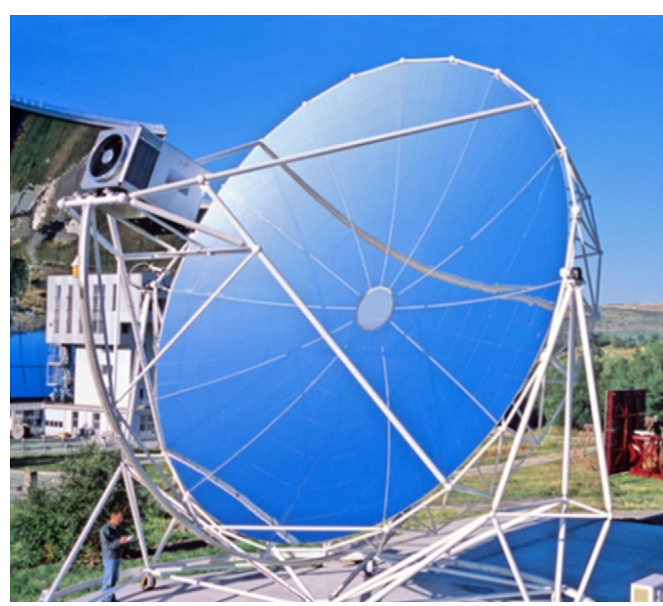

Fig. 6. Dish stirling CSP technology (10 kWe, PROMES laboratory France).

advantages of CSP technologies before PV ones (when stand-alone plants are under consideration) for which batteries still remain needed but undesirable in terms of both economical and environmental impacts.

Concerning the concentrating technologies available for CSP [1], only four are currently considered: (1) the solar trough concentrators [2–3] illustrated in Figs. 1 and 2, (2) the Linear-Fresnel concentrators [4] which are roughly a decomposition of the solar trough in multiple parallel plane mirror blades (Fig. 3), (3) the heliostats field associated to a central receiver tower (Figs. 4 and 5), (4) the dish concentrator (Fig. 6). Each of those different technologies presents its own advantages and drawbacks. Those aspects will be developed in & 2.2.

Compared to most of PV fields, a particular characteristic of CSP is the fact that the optic surfaces follow the sun during the day with respect to either one axis (Trough and Linear Fresnel) or two axes (Heliostats and Dish). Then, even if the solar tracking is still a non-obvious task, the whole daily and annual optical efficiencies of the CSP are significantly improved (but still limited to direct radiations while PV converts also diffuse solar flux).

In terms of historical development of actual CSP technologies, we can consider two major periods: (1) the 80's or the age of prototypes and solar trough industrial validation and (2) from 2000, the age of extensive industrial achievements followed by extensive R&D efforts.

Those two ages are illustrated in both Figs. 7 and 8 in which the different technologies are differentiated as well as pilot and industrial achievements. Even if most of the concentrating solar systems have been designed and tested very early (the first solar trough was experimented in 1870 in USA, the first Linear Fresnel pilot was built in France in 1926), the electrical power generation at industrial scale was really in the focus at the beginning of 1980's.

As illustrated in Fig. 7, during the first period, only the solar trough technology was developed at industrial scale in USA by successive additional plants (SEGS 1–SEGS IX) leading to 354 MWe running in 1990. As those plants are still today under operation, they have already achieved 20–30 years of production. This result leads to the acknowledgment of the solar trough technology as the most mature today from industrial point of view.

Before this success, the central receiver tower CSP approach was only developed at a pilot scale while the Linear Fresnel was totally absent.

Considering that Solar Two was a transformation of Solar One by the use of the solar salt HTF (heat transfer fluid) and storage

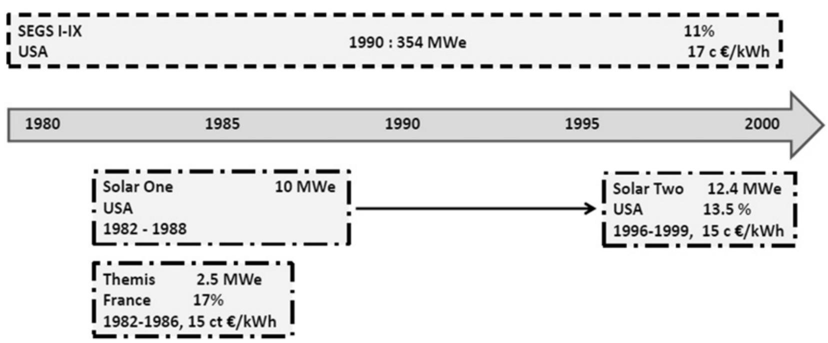

Fig. 7. First period of CSP development, the age of various pilot plants and solar trough industrial validation. Major: (- - -) industrial scale, (-. -) pilot scale, (above) solar trough, (below) CSP towers.

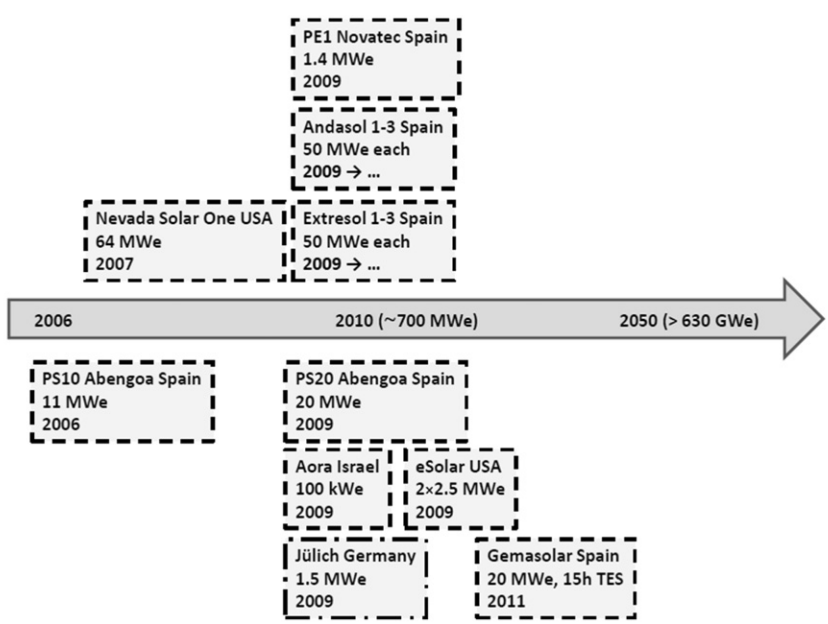

Fig. 8. Second period of CSP development, the age of industrial achievements and technology enhancements. Major: (- - -) industrial scale, (-. -) pilot scale, (above) solar trough, (above) Linear-Fresnel, (below) CSP towers.

developed at Themis instead of DSG (direct steam generation), we can roughly consider that nothing really new was built from 1986 till 2006.

Then, during 20 years, until 2006, the CSP was limited to the SEGS plants running and still R&D efforts under progress in the academic laboratories.

2006 is the beginning of a new age of CSP (illustrated in Fig. 8) with the operation of the PS10 (11 MWe, Abengoa Solar, Sevilla Spain) which historically was the very first central receiver tower plant built as an industrial process. This new achievement was quickly followed by major industrial realizations as Nevada Solar One in 2007 (solar trough, 64 MWe, USA), PS20 in 2009 (tower, 20 MWe, Sevilla Spain), Andasol in 2009 (solar trough, 50 MWe, Granada Spain) and numerous others and also numerous projects throughout several countries of high solar flux. One of the last most original one is probably PE1 which is a Linear-Fresnel industrial CSP, the very first one, in the form of modular (1.4 MWe) DSG system designed to use only low cost standard components and dry cooled power block. Another major recent achievement is the industrial Gemasolar solar tower plant (tower, 20 MWe, Spain, 2011) based on the Themis/Solar-Two technology but operating a 15 h storage allowing 24 h of continuous electricity production per day.

The Andasol and Extresol plants (both of Cobra company) are based on a modular approach with 50 MWe identical basic units to be duplicated. In each case, 150 MWe are planned by three successive lots. Already developed during the 80's for the SEGS plants, this very advantageous approach is not new. 50 MWe is already a large scale (even too large for most of the West African countries for instance) but taking into account the rather low thermodynamic efficiency of the solar trough (due to their low temperature level) a large scale is currently advised [5] to reach an economical optimum.

In contrary, the towers, which are able to reach highest temperatures (and then potentially highest thermodynamic efficiencies), could be seen as more relevant for small scale application even if they also can compete at large scale. ESolar and Aora tower plants are also modular systems but at very much lower scale (two modules of 2.5 MWe for eSolar and 100 kWe for Aora). Those technologies present a high potential for off-grid applications and can be advantageously applied also to large scales (connected to the grid as well). The eSolar philosophy is based on the fact that several small central receivers are much more secured than a unique large one as in case of failure of its key component, all the CSP plant would stop.

Among all these extensive industrial activities, the Andasol approach seems to be rather acknowledged as a standard in which the solar field is inherited from the SEGS technology (including the synthetic oil as HTF) and the thermal storage (based on a molten salt and two separate tanks to store the hot or the cold fraction) inherited from the Themis and Solar Two Tower pilots. Even if this whole process takes advantage of the major components validated during the 80's on both side (solar trough and tower), the various criteria and constraints to be considered to design such industrial processes have significantly changed in 30 years. As an example, environmental impacts, embodied primary energy or green house gas (GHG) as well as conflict of land use or matters or also water needs have become major concerns and have been proved to be able to stop the development of technologies.

Therefore, there is a need today to review those inherited technologies with respect to actual context in order to highlight major limitations or drawbacks to be seen as opportunities for further innovations.

Then, the following sections will deal with major technical issues according to the different major components involved in the whole process.

2. Major technical issues today

2.1. Solar energy resource assessment and identification of the energy needs

On the side of the solar resource, if numerous academic or industrial models and commercial tools are available today to calculate with some accuracy the solar course and extra atmospheric flux, it is still rather difficult to estimate properly the direct solar fraction available somewhere at the ground level. Very recently, at the last international Solarpaces conference [6], the major relevant worldwide specialists were once again concluding that significant advances are still to be achieved [7–9].

In this area, the corresponding development of sophisticated softwares will not be sufficient without enough available real ground relevant data. As a matter of fact, most of the solar belt countries do not have today the needed network of high quality meteorological measurement devices under operation. Moreover, when governmental or industrial organizations do have such data, they rarely agree to share them worldwide to help this task. As a positive example, Burkina Faso and Ghana in West Africa are under extensive development of such a network of measurements. In midterm, it is the whole West Africa which will be covered by this network.

In every case, before to decide the implementation of a large CSP on a land, the performance of the process has first to be estimated using simulations over a long period of several years. An estimation based only upon the best or the worst day of the year is not enough, and for similar complex solar process it has been shown that up to seven years of data could be needed to get relevant results [10].

Beside the solar resource, there is also a real need in identification of the local energy demands for various users (house, administration, and industries) in order to optimize the scale and the operation of the CSP plant. When existing, which is not obvious, such data usually belong to national companies who are, most of the time, not open to share them. Therefore, the potentially concurential renewable energy based plants suffer from a lack of data.

2.2. On the solar field

Technically, as illustrated in Figs. 9 and 10, the solar collectors are made of mirror surfaces supported on metallic frames. Even if those mirrors present today high optical properties (reflectivity of 95%, wide wave length reflectance) and if almost all kind of curvature or surface treatments can be realized, those are rather expensive (the solar field represent roughly 50% of the investment cost of a CSP plant) and fragile. Due to the weight of those mirrors and the surface they offer to the wind (Gemasolar heliostats present a surface of 120 m^2 each), an impressive metallic frame is associated as support (see Figs. 9 and 10) as well as concrete foundations to bear the whole system. Several attempts have been done to avoid this extensive use of metallic supports like concrete structure but without extensive industrial achievements.

Today, modern reflective products are available, deposited on all kind of light rigid or flexible supports. Those modern reflective materials have already their own commercial markets (for packaging and decoration industries) and then, they already present competitive prices (some euros per square meter) before the available CSP products. Those could lead to further innovative concentrating systems.

As the solar source is diluted, the so-called solar field is laid on a very large surface (200 ha in the case of the 50 MWe Andasol plant). According to the possible land use conflict, the solar field density needs to be optimized. This task is still not definitely

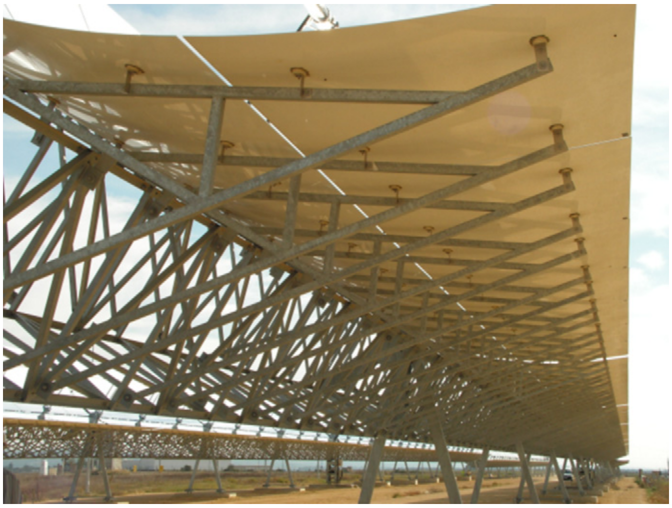

Fig. 9. Metallic structures needed to support the conventional concentrators, parabolic trough.

Fig. 10. Metallic structures needed to support the conventional concentrators, heliostats.

concluded. Solar trough concentrators are large enough to induce potentially light shading and blocking and then, large spaces have to be left between trough lines leading to solar field density of 26%. In the case of heliostats fields for central tower, the optimum solar field density is around 35% [11]. In the case of Linear Fresnel CSP, the density is higher but the optical efficiency is lower than the trough one. In this area, the approach of eSolar is based on rows of small heliostat units sharing the tracking units in order to reduce the cost, the time of solar field layout, the shading and blocking and the resistance to wind.

The maintenance of the solar field can be also seen as a key issue. As those CSP applications are usually to be implemented in sunny lands, they are very often built in dry lands covered by sand or dust. Therefore, while the direct solar flux is high, the optical efficiency is dramatically reduced by dust deposit on the reflective surfaces. Techniques are available to clean them using demineralized water or compressed air or more recently (in the case of Linear-Fresnel PE1) automatic motorized dry brushes. This aspect leads to an additional operating and water cost which could be not actually avoided. Then, R&D efforts are done today to find new techniques or specific coating to reduce the dust deposit.

As mentioned above, those reflective surfaces follow the sun at least partially. This supposes a solar tracking device, motors and moving parts. For those sub-components, extensive R&D efforts are still done. Every heliostat could be independent regarding its own tracking system or could be driven and managed by a central system shared by the entire field. Moreover, as those sub-components are rather expensive, there is today a real challenge between two major approaches: (1) big concentrating units to reduce the number of tracking and motors or (2) very small concentrating units placed on common racks to share sub-systems. The optimum is still under discussion.

To conclude on this major component, the recent implementation of the very first industrial Linear Fresnel CSP (EP1-Solnova, Spain) based on a simplified technology is certainly a significant signal. According to this achievement, recent studies [12] have shown that the life cycle analysis of the cheapest solar field (against trough) is really improved (less metallic support) and can be built in less time (major parts are assembled initially at the supplier manufacture plant and the minimum work is done on site). Every single element has been studied to be found as standard good available at low price on the market.

Even more recently, an extensive study [13] has been devoted to a complete life cycle analysis of conventional solar trough CSP and alternative dry approaches. According to this work, in the conventional configuration the solar field is responsible for 73%, 44%, 39% and 37% of the whole process GHG content regarding dismantling, construction, manufacturing and disposal life time steps respectively. It is also responsible for 72%, 44%, and 37% of the cumulative energy demand (CED) of the process in terms of dismantling, construction and manufacturing steps respectively. If all life time steps are considered, the solar field average contributions to the GHG and CED contents of the plant are 27% and 24% respectively. Then, the conclusions of this very recent and detailed analysis clearly comfort the above considerations.

2.3. On the absorber/receiver level

At low temperature range (200–500 °C for solar trough and Linear Fresnel), selective coating are deposited on the absorber tubes to get the highest absorbance of the incoming solar flux and the lowest infra red emitted flux. Then, the selective character of the absorber allows to reduce the thermal losses and consequently to increase the overall thermal efficiency. To enhance this effect, the absorber tube is usually surrounded by a glass tube to

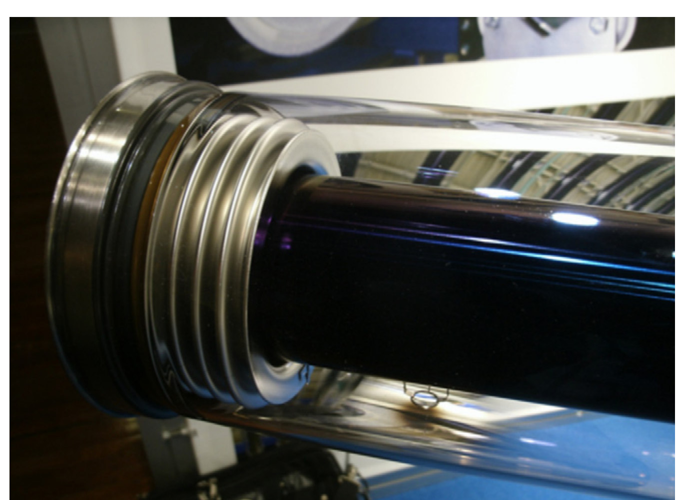

Fig. 11. Absorber surfaces needed for the conversion of the concentrated solar flux to thermal power, solar trough.

block its infra red radiations and to lower the convective losses. As an additional enhancement, evacuated volume between the two tubes is usually used to reach very low thermal losses and very high thermal efficiency (Fig. 11). Those selective coatings are currently obtained by electrolytic deposition of heavy metals containing species. Then, their costs are too high from both the economical and environmental viewpoints. Consequently, there is a need for cheaper selective coatings, with lower environmental impact (without heavy metals) and increased life time expectancy (30 years).

Complementary approach should develop environmental coating with eventually lower thermal efficiency but higher overall environmental balance.

At high temperature ranges (600–1000 °C for Dish-Stirling or central receiver towers), high temperature materials able to stand thermal constrains as well as oxidative environments are usually expensive. Those materials as ceramics like SiC or metals like inconel are currently used at laboratory or pilot scales [14] but could be too expensive at industrial scale. Consequently, there is a need to look for absorber surfaces that could be able to resist to hot air upto 1000 °C. A thorough focus must go to new receiver design avoiding glazing and simultaneously reducing heat losses (convective and radiative losses), a receiver material able to stand thermal shocks and compatible with high temperature HTF. Historically, most of the central receiver absorbers were simply made of high temperature (non-selective) paints over metallic tubes in which water was heated and evaporated (Solar One, PS10, PS20) or molten salts were heated (Themis, Solar Two). This simple and rather inexpensive technology illustrated in Fig. 12 in the case of Themis is still used today (PS10, PS20).

Fig. 12. Absorber surfaces needed for the conversion of the concentrated solar flux to thermal power, Themis central receiver (France).

2.4. On the HTF side

In Table 1 major available HTF for CSP are gathered with their respective properties for comparison.

At the lowest temperature range (below 200 °C), extensive efforts are done today to develop new thermodynamic systems using organic fluids allowing even to use non-concentrated solar collectors. Usually, those systems concern small scale facilities from 10 to 100 kWe but have been already tested historically at larger scales.

Upto 400 °C, the major fluid widely used in solar fields based on parabolic trough is the so-called solar oil. This synthetic oil (biphenyl oxide) is expensive (about 6 euros/L), highly hazardous (environmentally and very flammable), subjected to industrial monopoly and strictly limited below 400 °C.

According to the solar trough CSP life cycle analysis [13], the solar oil contributions to the whole GHG content of the process represent 24%, 22% and 21.4% in terms of disposal, operation and manufacturing respectively. Similarly, its contributions to the CED of the whole plant are 27%, 24% and 15% in terms of manufacturing, operation and dismantling. Therefore, the so-called solar-oil remains one major contributor (21–23%) to the environmental impact of the CSP plants.

Then, there is a need in new HTF which should be environmental friendly, stable, not subject to solidification under ambient temperature and available at low cost without conflict of use. They could be enhanced in terms of heat transfer conductivity (by adding nanoparticles) and thermal capacity (micro-PCMs). Major efforts are done worldwide today concerning those new composite fluids.

According to those considerations, from low to medium temperature ranges the best available fluid would remain water/steam. Nevertheless, to allow DSG (Direct Steam Generation) technologies to be developed, there is a need in new absorber tube or receiver designs to control properly the L/G (liquid/gas) phase change stage. As a matter of fact, PS10 first industrial solar tower and PE1 first industrial Linear-Fresnel plant are based on DSG. In the last one, a secondary reflector is used to light the absorber tube which is insulated on its upper side and also prevented from the IR lost using a glazing on its lower side.

At higher temperature ranges (upto 600 °C), molten salts have been proved to be very efficient HTF. In the field of CSP applications, only nitrate combinations are used: the so-called solar salt

Table 1
Heat transfer fluids (HTF) used in concentrated solar power plants.

HTF	Plants	Maxi T (°C)	Drawbacks	Advantages	ρ, C_p, λ, μ (at operating T)
Mineral oil	SEGS I–III	< 400	Inflammable	Good perf.	equ.synth.
Synthetic oil (Therminol VP1) 390 °C	SEGS > III Andasol Extresol	< 400	Inflammable Highly toxic expensive	Good perf.	709 kg/m^3 2588 J/(kg K) 0.078 W/(m K) 0.152 mPa s
Water/steam 250 °C 40 bars	Solar One PS10, PS20 PEl	–	High T leads to high P and cost	Cheap HTF inert	Depend T, P
Moten salt (nitrates)	Themis Solar Two	600	Corrosion freezing point	HTH and storage media	900–2600 1500 0.15–2.0
Air (700 °C)	Julich	–	Low performances	Cheap	Depend T, P

60% $NaNO_3$–40% KNO_3, the Hitec XL 48% $Ca(NO_3)_3$–7% $NaNO_3$–45% KNO_3 and the Hitec 40% $NaNO_2$–7% $NaNO_3$–53% KNO_3. As a matter of fact, their major advantages are to be industrially available and acknowledged as HTF for a long time, they can be used simultaneously as thermal storage material and they are operated close to the atmospheric pressure. Their major drawbacks are due to their crystallization temperatures which are significantly above the ambient temperature (142 °C for the Hitec, 150 °C for the Hitec XL and 250 °C for the solar salt) leading to possible freezing and plugging. Major efforts are done worldwide today to reduce the freezing point of those HTF. Molten salts have been early used as HTF in Themis and Solar Two pilot plants during the eighties. Very recently, they have been used again with success as HTF in the solar field of Archimede (5 MWe, parabolic trough, Sicily, 2010) and in the Gemasolar tower (20 MWe, heliostats central receiver, Spain, 2011).

At very high temperature range, air is the sole available fluid (eventually He, CO_2 or H_2 in Dish-Stirling systems). In this case, very high temperature levels can be reached (600–1000 °C) allowing to feed gas turbines; but corresponding high temperature receivers materials are still needed. Initially, the PS10 industrial CSP tower was planned to involve such HTF [15] but it was finally shifted to a low temperature DSG one. Very recently, a first demonstrating experimental tower has been operated in Jülich-Germany [16] using air at 700 °C, a steam turbine and a ceramic based storage with a nominal power of 1.5 MW. The future success of this first very high temperature CSP pilot will probably open the technology to industrial achievements at larger scales.

2.5. Thermal energy storage (TES)

The available current industrial approach is based on the two tanks molten salt systems inherited from the eighties (it was already inherited from 50 years of practice in chemical or metallurgical industries at that time). This storage represents roughly 19.5 and 18% of the embodied GHG and CED of a solar trough based CSP [13–17,18] and 15% of the whole investment. Its major contributions to the environmental impact of the whole plant are due to the construction (37% in GHG, 37% in CED) and the disposal (33% in GHG, 90% in CED) steps [13]. Despite these facts, it is the unique mature available TES technology at large scale. In the Andasol CSP plant (first operated in 2009), 28,000 tones of molten salts are used to deliver 7.5 h of thermal storage. Today, this CSP plant is considered as an industrial standard and numerous copies are already built or under implementation. Even more recently (2011), the same TES technology has been applied to the solar tower power plant of Gemasolar with 15 h of storage capacity allowing 24 h of full operation per day.

By the way, according to IEA experts, 20 GWe of CSP are globally needed to be built every year until 2050 to meet the international energy policy targets. This would represent 400 Andasol plants every year and therefore 30 times the production of the main producer (the Chile mines) per year. Furthermore, the current storage material is already worldwide used in the chemical industry (70%) and in agriculture (30%). The corresponding synthetic nitrates would lead to higher investment costs as well as worse environmental balance. Then, an extended use of nitrate molten salts in CSP thermal storage would lead to a major "conflict of use" (which was the end of the first generation of "green" fuels) and anyway, the current production would cover only 3% of the CSP needs.

Moreover, in European countries, the amount of molten salt associated to the highly flammable "solar oil" leads to a SEVESO classification usually reserved to dangerous chemical processes (see section 3 on policy issues).

Therefore, there is a need in alternative approaches considering other materials for large scale storages. This could be based upon natural materials like rocks but those materials have proved to be sometimes responsible for the enhancement of the HTF degradation due to catalytic effects.

Recently, sand has been also proposed as HTF and storage material for tower CSP and is still under current study in Germany [19].

An alternative approach to those natural sensible heat materials is proposed by the DLR [20]. It consists to use high temperature concrete modules in which a steel heat exchanger is embodied through which the HTF will flow. A major advantage of this technique is the large availability of the material and its relative low cost (about 80 euros/ton). This system has been validated but it is limited to 500 °C and its life time is still lower than expected (10 years, less than the 40 years of CSP plant life time). Moreover, the heat exchanger represents a significant overcost and could be hardly recycled.

An original approach has been proposed recently [21] which is to recycle end-of-life materials produced by industrial vitrification treatments of wastes as TES media and to shape directly the molten inerted product at the outlet of the treatment as TES modules. A successful illustrating example is the Cofalit, a ceramic made by plasma-torch vitrification of Asbestos containing wastes. The approach has been already extended to other worldwide available wastes such as Fly-Ashes [22] leading to similar refractory ceramics. The use of those materials as TES media allow a pay-back of the energy needed for their treatment and a real valorization leading to new commercial uses.

This Sustainable TES approach (STES) is under development at different stages: current industrial treatments of Asbestos containing wastes are modified for the direct manufacturing of TES modules, optimized TES modules are designed and under manufacturing to be tested at pilot scale for CSP and CAES applications.

Considering that future CSP processes should be probably based on DSG, sensible heat based TES would present thermodynamic limitations. Therefore, extensive researches are needed in other TES technologies allowing thermodynamic temperature control like those using Phase Change Materials (PCM) or thermochemical concepts. In the particular case of PCM materials, the heat is stored and released by fusion and solidification of an inorganic salt or eutectic. High amount of heat can be stored by units of mass or volume but PCM present too low thermal conductivity (between 0.8 and 2 $W\,m^{-1}\,K^{-1}$) to get the needed thermal power. Then, various technologies are proposed like those using conductive composites [23] or metallic fins [24]. Those approaches lead to high performances but also to high costs. Then, large scale TES for CSP of several hours could be hardly based on those technologies which should be limited to reduced TES capacities.

Thermochemical TES approaches are still under studies at laboratory scale only. They lead generally to too complex and expensive systems.

2.6. Hybridation and/or co-production

As an alternative to thermal storage, one can use a fuel fed boiler when the solar resource income is not available or below a critical level. This task is usually fulfilled by using natural gas or petroleum oil. For years, numerous authors have proposed other hybridation using more environmental fuels like wastes from wood or from agriculture industries [25]. Up today no industrial plant is running by such a hybrid system due to the high risk in lack or fluctuation in availability and price variations of the

Fig. 13. Jatropha culture in Burkina Faso.

co-resource during the 40 years of the CSP plant expected lifetime. Then, this very attractive option could be realistic only if the CSP plant operator can secure the co-resource incomes and price for 40 years.

In this area, the land which is used in a large extend to implement the needed solar field with a rather low coverage could be advantageously shared to produce simultaneously biofuels. Below and between the mirrors, plants could be co-produced taking advantage of partial shading in desert areas. In exchange, the reflective surfaces will take advantage of less dust from the ground. The overall system would produce, at least partly, its own biofuel needed for hybridation and offer more labors to the local populations.

In this particular area, the 2iE institution based in Burkina Faso develops for years, in collaboration with the CIRAD (France), extensive researches [26–27] and several plants are already available throughout the West African countries: Jatropha (Fig. 13), cotton stalks, rice ball, cashew…. The corresponding processes of oil extraction and filtration as well as the modification of diesel engines have been also assessed. Then in West African countries, populations can produce today their own biofuel and run a multi-service engine for water pumping, grinding and all kind of activity for which mechanical energy is needed (including the extraction process of the biofuel itself).

As an illustrative example, the 200 ha of the Andasol solar field (corrected by the solar field density) could produce almost 355 tones of Jatropha biofuel per year (an average of 2.4 tones/ha of Jatropha oil is produced per year). Moreover, the Jatropha oil can produce upto 38.8 MJ/kg [27] leading to 13,774 GJ/year. Considering that a 200 ha CSP plant needs 150 MW of heat to produce 50 MWe, only 25 h of nominal power could be really supplied by the Jatropha yearly production. Therefore, this oil has to be seen as a co-product to be used for other needs or has to be completed by additional biofuel produced elsewhere. Nevertheless, the major advantages mentioned above associated to the opportunity to offer a co-production of solar electricity and biofuel (to be used in all kind of diesel engine) are very attractive for West African countries.

2.7. Water consumption

According to the SEGS experience, the water consumption of water-cooled solar trough is 1 Gal/kWhe, 93% for steam condensation of the Rankine cycle. In such a system, a cooling tower, which is today the most efficient technology, is used to condense the vapor at 60 °C at the outlet of the turbine (Figs. 1 and 3). The alternative available technology today is based on the use of dry coolers composed of electrical driven fans flowing ambient air through tubular finned heat exchangers. This condensing mode is applied today in PE1, consumes no water but is responsible of a significant decrease in the overall efficiency. Moreover, according to this particular configuration, the lower temperature level of the steam cycle is dramatically function of the external ambient temperature (which is quite high in desert areas and too close to the 60 °C of condensation). Globally, the production of electricity is lowered by 5% and its cost increased of 7–9%.

In a recent study [13] wet and dry solar trough CSP plant configurations have been deeply compared. According to this work, if the dry technology allows reducing the water consumption by 77%, it induces dramatically GHG emissions and CED by 8%.

As a recent practical illustration, two CSP plants projects have been canceled in western USA because of their potential water consumption equivalent to 10–15% of the local water resource. In this case, the potential conflict of water use has been the key issue in the debate.

Therefore, there is an urgent need in new dry and efficient cooling systems and recent calls have been made at the European and International levels for research on this field. Already some new approaches have been proposed using wet–dry hybrid systems (in which wet cooling is used only during the hottest hours), solar chimney (by which the fatal heat is transformed into electricity) or thermal storage associated to free cooling (taking advantage of the cooler temperature of the night) [28].

Even if mirrors cleanness is much less water consumer, some 1.5% of the total SEGS water consumption is associated to mirror cleanness, efforts have been made to reduce this need of very pure water. In the particular case of flat mirrors like PE1, automatic dry brush robots have been developed and used today. For curved surfaces, techniques based on compressed air are also developed.

Therefore there are needs in new reflective surfaces in the solar field with reduced cleaning maintenance.

Viewed from West Africa region, as shown by [29], water resource assessment of a candidate site for CSP plant is paramount in deciding on the mode of cooling; it is more so for the Sahel zone (Niger, Burkina, Mali…) where rainfall pattern is erratic, where water bodies are scarce and where dust deposits from the Sahara desert are quite significant. For instance, in the suitable region of Burkina Faso (Sahel region in north of the country) for CSP implementation, the total length of the rivers is around 23,000 km. Some rivers have continuous flow, others do not. The region has thirteen rivers out of which ten are temporaries and three are permanents. The region has 76 lakes out of which 58 are natural and 18 artificial. The rainy season, very unstable, runs from June/July to September/October; and the dry season can last 9–10 months with temperatures that vary between 10 °C and 43 °C. It is clear that this area is poor in water resources. And that is the situation for almost the Sahel area of sub-Saharan Africa (Niger, Mali, north of Nigeria and Burkina, Mauritania….) where there is a good solar irradiation.

In another very different approach, CSP technologies can be advantageously used to produce drinking water instead of consuming it [30,31]. Extensive researches have been made already to use the waste heat of the condenser to drive MED. Then, instead of consuming drinking water, the CSP plant produces it as a co-product. It can be even more advantageous economically to use the solar produced electricity to drive reverse osmosis when desalinated water is more expensive than electricity in the local market. Then, in this case, the whole CSP process is devoted to the production of drinking water. For all of these approaches, the hybrid system is potentially based on the combination of conventional CSP and conventional desalination processes. Nevertheless,

as in the case of CSP, the conventional desalination processes inherited from the 80's present major drawbacks before today's constraints. Their energy consumption and their environmental impact are both too high. Therefore, hybrid systems of CSP associated to desalination or purification processes would be highly appreciated but with new sustainable approaches for both of them.

2.8. Energy transport and distribution

CSP technologies can be used to produce small (10 kWe) upto large (350 MWe) electric power. Then, it can be considered for all kind of local needs, from a small off-grid house to a large European or Western kind city.

According to these particular situations, the CSP process has to be first thought considering many aspects such as the presence of grids (as in France where the available one is not particularly adapted) or the absence of grid (like in a major parts of Africa), the shift between the electric demand and the potential production (a thermal storage would be generally needed), the presence of existing concurrent electricity producer and the governmental energy strategy.

In the case of France, the metropolis has a current grid built initially for centralized production based on very large scale nuclear power units in the range of GWe assisted by lower scale fossil power units. Then, the integration of renewable energies presents for this country a rather difficult task. For the same country, considering its overseas territories like Corsica or La Reunion, most of them are in the same case of West African countries. For example, Corsica is today very active in the field of R&D devoted to micro-grid, renewable integration, hybridations and energy storage as well.

2.9. Implementation, operation, maintenance, dismantlement

In most cases, CSP plants result from the association of basic components (namely: the solar field composed of reflectors and supports, the absorber collector tubes or the receiver, the storage system, the power block,…), made by independent suppliers who eventually joint together in a consortium. Then, the selection of components, their supply, implementation (including the land layout) and the start of the whole system have to be considered as real issues in term of industrial activity. In this field, progress could be probably gained to reduce the whole time needed to reach the plant first operating level.

In another field, the operation and maintenance of such a dynamic process during the 30–40 years of life time are also very specific. Even if major components of the plant are similar to those of any thermal power systems, the solar resource imposes to them very particular constraints and behaviors. The operator has to take into account the solar resource fluctuations at different levels, to protect the components against too strong variations but also to secure the production at a stable level.

Today, the conception of a renewable based industrial process is also to be considered in terms of dismantlement and recycling of the materials and fluids. As highlighted above, some specific components such as solar field, HTF or TES present today too high GHG and CED impacts concerning these issues [13]. This is not an obvious issue and it will be the opportunity in the future for development of specific industrial activities.

3. Major policy issues

In terms of policy, the European countries still present large variations. Sometimes, policies decided for a particular renewable energy are directly applied to others leading to strong and unadapted limitations. As an example, any kind of solar power plant is limited to a scale of 12 MWe in France. This rule first applied to PV has also to be observed for CSP while all international and national experts know that any relevant industrial scale for this technology is in the range of 50 MWe. In another area, the combination of use of both the synthetic "solar oil" in a solar trough field (a combustible) and the molten salts in the storage system (a comburant) has lead to a SEVESO classification in France and consequently to the abandon of an industrial project. In the same time, and now several times, similar combinations are implemented in Spain without so much attention. As several fires have been already observed in the Andasol solar field, the potential hazard could not be seen as unrealistic and DSG has to be highly recommended.

The current renewable energy policy situation in Africa in general is highly crucial (especially in sub-Saharan Africa). In fact, particularly in West Africa, apart from Ghana where the Renewable Energy law is discussed before parliament and Niger where a law on renewable energy is currently being formulated, the other West African countries do not have any explicit regulation/legislation neither for Renewable Energy in general or for solar energy in particular. Some countries like Niger and Nigeria have formulated a national renewable energy strategy or Renewable Energy Master Plan. However, many countries offer tax exemptions for solar energy products.

It was against this background that Regulation C/REG.23/11/08 of the 61st Session of ECOWAS (Economic Community of West Africa States) Council of Ministers in Ouagadougou, Burkina Faso, established ECREEE (Regional Centre for Renewable Energy and Energy Efficiency) on November 23, 2008. One of the objectives of ECREEE is to develop, at the regional level, policy and regulatory frameworks which should be adopted by the member states as an ECOWAS renewable energy protocol (e.g. regulations, codes, quality standards).

4. Conclusions

Concentrated Solar Power has experienced a first historical development during the 80's followed by a new industrial extensive interest at the beginning of the XXIst century. This industrial way to produce electricity from the sunlight is acknowledged today among the alternative renewable energy based processes able to substitute the fossil resources in the future.

Nevertheless, numerous improvements have to be considered for these technologies.

Several components of CSP plants could take advantage of new materials and new concepts to reduce their costs and environmental impacts and enhance their performances. This is specifically the case of concentrating optical components, absorber tubes, thermal storage material or heat transfer fluids.

Other components were optimized according to the 80's constrains but do not satisfy today's ones. This is the case of thermal storage or heat transfer oils.

Moreover, those processes are particularly suited to solar belt countries for which the solar resource is not always well assessed today and where those available technologies are not always adapted (in terms of scale or materials and equipments).

Therefore, CSP technologies are real opportunities for industrial countries like European ones which could develop companies devoted to the whole process as well as specific companies devoted to particular components even if those countries are not in the solar belt. Moreover, CSP is also a real opportunity for solar belt countries like in Africa to become the future electricity suppliers of northern countries and also to reach their own

electricity autonomy. This is particularly the case of Burkina Faso, a West African country without fossil resources but having today simultaneously the needed academic support and a strategic regional geographic position.

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